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The Determination of the Effective Radius of Drops in Water Clouds from Polarization Measurements

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Abstract. A study of the influence of the solar angle, thickness, and microstructure of a cloudy medium on the intensity and the degree of polarization of the reflected solar light was performed in the framework of vector radiative transfer theory. Calculations were carried out for water clouds for wavelengths of 443, 670 and 865 nm. The solar angles were varied in the range 0-90 degrees. It was found that the rainbow polarization is larger for larger particles. The position of the rainbow shifts to larger scattering angles with decreasing particle size. The degree of polarization decreases with the optical thickness and reaches an asymptotic value for semi-infinite clouds at an optical thickness of about 100. A new method for the retrieval of optical thickness and the effective radius of water drops at a single wavelength is proposed. This method is based on the measurements of the intensity and the degree of polarization of the reflected light at the rainbow angle. Such measurements are important also for the discrimination of ice clouds and snow fields on satellite images due to the fact that ice clouds and snow do not show enhanced scattering at the rainbow angle.

I. Introduction

The problem of the determination of the size of particles in turbid media is of importance for different branches of modern science and technology, including clouds microstucture studies from space. It is a well known fact that water clouds are important regulators of shortwave fluxes in the Earth atmosphere. Their influence on the intensity of solar radiation, coming to the Earth, was investigated in numerous papers and books [1-17]. Another important feature of clouds, namely their ability to change the polarization characteristics of incident radiation, was studied in detail as well [18-21]. This knowledge was applied to the solution of the broad spectrum of inverse problems [2, 3, 5, 7-9, 11, 15, 17, 22-25]. For instance, it was found [18, 25] that rainbow scattering can be used to determine the thermodynamic phase of clouds. Such a determination is based on the fact that the presence or absence of rainbows depends on the shape of particles in a scattering medium [18, 25-27]. A rainbow does not exist at all for ice clouds which are collections of highly nonspherical particles of different shapes [3, 18, 26]. This feature has already been used in satellite retrieval algorithms [25]. It could be applied for the discrimination of cloud and snow fields on satellite images as well.

The main task of this paper is to show that the rainbow scattering can be used not only for the detection of the shape of particles, but also for the determination of the effective radius of particles a_{ef} and the optical thickness τ of turbid media. Some results in this direction have already been reported by Breon and Goloub [28].

With this in mind extensive calculations of the degree of polarization and the reflection function of cloudy media were performed at wavelengths 443, 670 and 865 nm. These values correspond to channels (with the possibility to measure the Stokes vector components) of the POLDER radiometer on board the Japanese ADEOS-II satellite.

II. Radiative and polarization characteristics of water clouds

Polarization characteristics of light, reflected from turbid layers can be obtained in the framework of vector radiative transfer theory [2, 13, 29]. To do so one should solve the vector radiative transfer equation with corresponding boundary conditions [13, 19-21]. The most simple and transparent results can be obtained for normal illumination of a layer or for nadir viewing geometries. These permit reduction of the number of Stokes parameters to be calculated and analyzed. For instance, the Stokes vector of the reflected solar radiation does not depend on azimuth at nadir viewing angles. Moreover, the third and forth components of the Stokes vector are equal to zero due to the symmetry of the problem. Thus,

the reflected radiation is partially linearly polarized with degree of polarization P. The electric vector of the reflected light is in a plane which is defined by the normal to the light-scattering layer and the direction of the reflected light ($P<0$) or in the direction perpendicular to this plane ($P>0$). We found that for most incidence angles the value of P is positive and the reflected radiation is partially linearly polarized in the direction perpendicular to the meridional plane. The degree of circular polarization is equal to zero. This approximately holds for near nadir measurements as well.

Our calculations were performed with a vector radiative transfer code, based on the doubling method of radiative transfer theory [13, 19, 30] at different light incidence angles and the near nadir viewing angle $\vartheta = 2^\circ$. The relative azimuth φ was equal to zero. Some results of the calculations are presented in Figs. 1, 2.

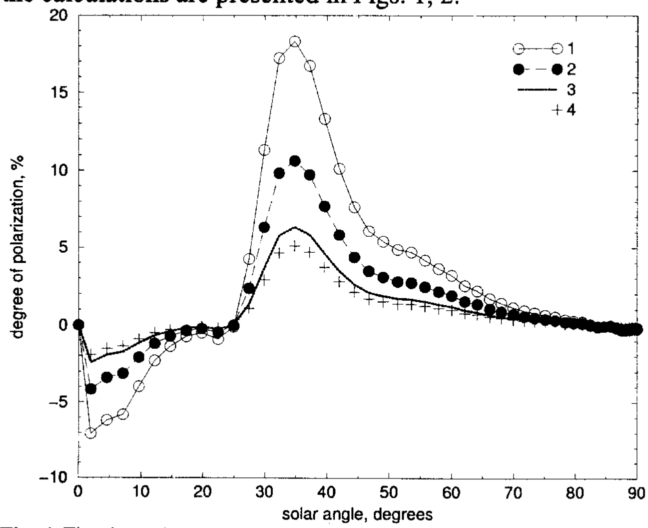

Fig. 1 The dependence of the degree of polarization of light reflected from water clouds on the incidence angle at $\lambda = 865$ nm, $\vartheta = 2^\circ, \varphi = 0^\circ$, $a_{ef} = 6$ µm, and $\tau = 5(1), 10(2), 30(3), 100(4)$.

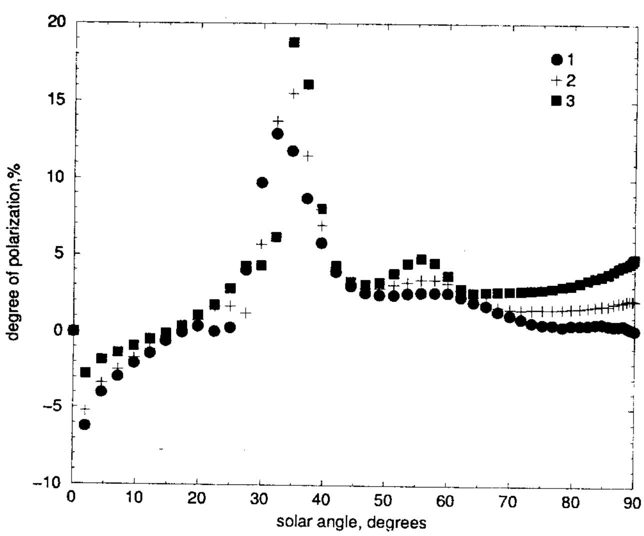

Fig. 2 The same as in Fig.1, but at $\lambda = 443$ nm, $\tau = 10$, and $a_{ef} = 4$ (1), 6(2), and 12(3) µm .

Generally speaking, the reflection function and degree of polarization of the light reflected from a turbid layer for a fixed observation geometry depends on its optical thickness , size of particles , and their refractive index. The effective radius of the particles a_{ef}, defined as the ratio of the third to the second moment of the particle size distribution, is in the range 4 – 16 µm and the optical thickness τ is in the range 5 - 100 for most of water clouds. For instance, during the experiment[11] it was found that the optical thickness of clouds was in this range with the most probable values approximately equal to 10. Thus, we performed calculations at the optical thickness $\tau =$ 5, 10, 30, 100 for the values of a_{ef} equal to 4, 6, 8, 12 and 16 µm. The incidence angle was varied from zero to 90 degrees. We used the following particle size distribution to find the local optical characteristics of cloudy media with the Mie theory [19]:

$$f(a) = Ba^6 \exp(-9a / a_{ef}),$$

where B is the normalization constant($\int_0^\infty f(a)da = 1$).

The dependence of the degree of polarization on the optical thickness of a layer and the incidence angle ϑ_0 is presented in Fig. 1. One can see that the polarization decreases with the optical thickness. It has a peak, which corresponds to the rainbow scattering region. The dependence of $P(\tau)$ can be used for the determination of the optical thickness of clouds from polarization measurements. The most sensitive angles are in the range of rainbow scattering. It should be pointed out that this technique would be of importance only for small and moderate values of the optical thickness. The degree of polarization only weakly depends on the optical thickness for thick layers. It rapidly approaches its asymptotic value for a semi-infinite medium.

The dependence of the degree of polarization on the size of particles is presented in Fig. 2. One can see that larger particles are responsible for larger values of the degree of polarization inside the rainbow peak. The maximum of polarization moves to smaller scattering angles with increasing size of the droplets.

III. Rainbow polarization as a tool for particle sizing

The dependence of the degree of polarization at the rainbow angle, on the value of a_{ef} can be used for the solution of the inverse problem of cloud optics. In the framework of this new retrieval method one should measure the values of the reflection function and the degree of polarization at the rainbow scattering angle, which is defined by the following equation [31]:

$$\theta_r = \pi + 2\arccos\left[\sqrt{\frac{n^2-1}{3}}\right] - 4\arcsin\left[\sqrt{\frac{4-n^2}{3n^2}}\right].$$

This angle depends on the refractive index n of the particles, which is different for different wavelengths. One can find that the rainbow angle is equal to 138.5, 137.6, and 137.2 degrees for wavelengths equal to 443, 670, and 865 nanometers respectively. Thus, the rainbow shifts away from the backward direction with wavelength.

It was found that the reflection function only weakly depends on the size of droplets in visible. This feature is attractive for the optical thickness retrieval, as was discussed by King [11]. The measured value of the degree of polarization for the optical thickness τ, found from reflection function measurements, can be used to estimate the effective radius of the droplets (see Figs. 2, 3).

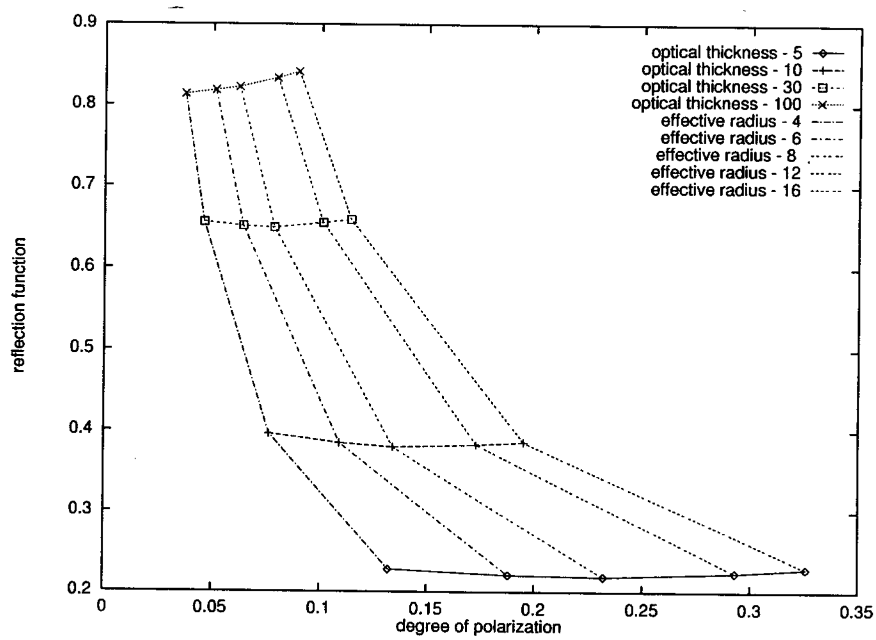

Fig. 3 The reflection function and degree ofpolarization of light reflected from water clouds at different values of the optical thickness and effective radius of droplets for a wavelength of 670nm (nadir observation, $\vartheta_0 = 36^\circ$).

Note that values of θ_r, obtained from the equation presented above, are approximate and do not depend on the size of the particles. In reality the position of the rainbow is shifted and this shift is proportional to the value of $\left(\frac{\lambda}{a_{ef}}\right)^{2/3}$ [31,32]. This follows from Fig. 2 as well.

To find values of the effective radius and the optical thickness one should construct special look-up tables for degree of polarization and reflection function of clouds at different a_{ef} and τ and viewing geometries [17]. After that, the size of droplets and optical thickness can be calculated from the minimum of the following function:

$$F = (\ln R_m - \ln R_c)^2 + (\ln P_m - \ln P_c)^2,$$

where R_m, R_c, P_m, and P_c are measured (m) and calculated(c) reflection functions and degrees of polarization respectively. The values of a_{ef} and τ can be found separately at $\tau > 30$, because the curves in Fig.3 are nearly orthogonal for thick clouds. Moreover, the reflection function is almost independent of the optical thickness as $\tau \to \infty$. Thus, the value of a_{ef} can be found from measurements of $P(\theta_r)$ alone in this specific case. It is interesting that the maximum of the rainbow shifts to smaller solar angles with decreasing particles sizes (see Fig. 2), making the degree of polarization at the rainbow angle more sensitive to the radii of droplets. This improves the retrieval accuracy.

The method proposed is readily generalized for any viewing angle. The viewing angle ϑ, the relative azimuth φ, and the solar angle ϑ_0 are related by the following equation [29]:

$$\cos\theta_r = \sin\vartheta \sin\vartheta_0 \cos\varphi - \cos\vartheta\cos\vartheta_0$$

at the rainbow geometry. At $\vartheta = 0$, one can obtain:

$$\vartheta_0 = \pi - \theta_r.$$

IV. Conclusions

A method for the determination of the size of water droplets in clouds is proposed. The chief shortcoming of the retrieval algorithm proposed is that it needs a special geometry for the measurements (rainbow scattering). One way around this problem is multidirectional measurements, which are performed by the POLDER instrument [25].

The effective radius, obtained with this approach, is not representative of the total geometrical depth of the cloud. The value retrieved is mostly related to the microphysical parameters of the cloud top. This is also the case for the particle sizing approach of Breon and Goloub [28], based on measurements of light reflection and polarization in the region of secondary rainbows. The information obtained with the rainbow scattering technique could be of value in addition to results obtained with the use of spectral signatures of water clouds [8].

Note, that the accuracy of the retrieval can be improved if one performs spectral measurements of the degree of polarization at the rainbow angle. The angular distance between secondary and primary rainbows also provides additional information on the cloud microstructure.

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